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CONSTITUTIVE MODELING FOR SINGLE CRYSTAL SUPERALLOYS*

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INTRODUCTION

Single crystal superalloys are a two phase γ-γ' alloys with a large volume fraction of γ'. The γ' precipitates have a L_{12} cubic crystal structure and are distributed in a coherent face centered cubic γ solid solution.

The mechanical response shows significant variation in the mechanical properties with orientation and temperature. Near 700°C the orientation dependence is most severe and a tension-compression asymmetry up to 50% has been observed in PWA 1480 (Ref. 1). The minimum creep rate typically varies by a factor up to 100 with orientation for fixed values of stress and temperature. Above 700°C the orientation dependence and tension-compression asymmetry decrease with increasing temperature. Significant strain rate dependence is observed at the higher temperatures and some cyclic hardening is also observed.

The constitutive model to be developed for the material must accurately predict the response, must be efficient in finite element calculations and should be easy to relate to experimental data so the material parameters can be reasonably determined. Specifically, the following features must be included in the model for single crystal superalloys:

- Orientation dependence
- Tension-compression asymmetry
- Temperature dependence
- Time and rate dependence

It is expected that the model should predict monotonic, fatigue and multiaxial (proportional and nonproportional) loading. At the present time the following effects are not included:

- Large strain and tertiary creep
- Slip bursts
- Coating-substrate interaction.

The current status of the work is reported in detail in Reference 2.

CONSTITUTIVE MODELING APPROACH

A crystallographic approach to constitutive modeling is adopted. The approach is based on identifying the active slip planes and slip directions. The shear stresses are computed on each of the slip planes from the applied stress components. The slip rate is then computed on each slip system and the macroscopic inelastic strain rates are the sum of the slip in the individual slip systems.

The classical assumption of Schmid's law (slip is a function of the resolved shear stress in the slip direction) is not adequate for γ-γ' alloys since it cannot explain the observed tension compression asymmetry. More recently, Lall, Chin and Pope (Ref. 3) showed the tension-compression asymmetry is controlled by cross slip which depends on the stress perpendicular to the direction of propagation of two Shockley partial dislocations. This stress tends to extend or constrict the partials and inhibit or promote cross slip, respectively.

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The constitutive model at the crystallographic level is based on the Bodner inelastic flow and hardening equations (Ref. 4) but is modified to incorporate the results of Lall, Chin and Pope. The formulation is valid for coupled octahedral and cube slip and has been extended in an attempt to include both the shear and diffusion mechanisms.

FINITE ELEMENT IMPLEMENTATION

The constitutive model was implemented in a finite element code using twenty noded isoparametric solid elements. This element was chosen since it can be used to model almost any three-dimensional geometry allowing for any orientation of the principal material axes. Order two Gaussian integration was used for stiffness generation and calculation of the body forces. The ability to represent piecewise linear load histories was also incorporated. This is particularly useful for modeling fatigue loops and other specialized load histories. Since the inelastic strain rate can change dramatically during a linear load history a dynamic time incrementing procedure is also included.

EXPERIMENTAL DATA

The constitutive model and finite element code (two elements) were used to predict the response of Rene N4. The experimental response at 760^{o}C was used since the orientation dependence and tension-compression asymmetry is most severe near this value. Unfortunately, the data base is limited and the calculations were done for two specific alloys reported in the literature. At 760^{o}C the stress-strain response in tension and compression and fatigue response was determined by Gabb, Gayda and Minor (Ref. 5) for several orientations. In another report (Ref. 6) the tensile and creep response at three orientations was reported for Rene N4 with a slightly different chemistry. Since the response characteristics of the two alloys were significantly different they were modeled independently. However, both systems were modeled to test as many properties of the constitutive theory as possible. A method has also been developed and for determining the material parameters from the experimental data.

CALCULATED AND EXPERIMENTAL RESULTS

The constants were determined for octahedral and cube slip systems for the data reported in Reference 5. These constants were then used to predict the tension-compression asymmetry and fatigue loops as shown in Table 1 and Figure 1, respectively. The other data set was used to model the tensile and creep response. The experimental and calculated tensile response is shown in Figure 3 and a sample creep prediction is shown in Figure 4.

FUTURE RESEARCH

During the next year much of the analytical effort will be spent in software development, refining the constitutive model and extending it to other temperatures. An experimental program is under way to determine response characteristics in tension, creep and fatigue at five orientations and three temperatures. Microscopy will also be included to determine the active slip systems and deformation mechanisms.

REFERENCES

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TABLE 1. COMPARISON OF MONTONIC YIELD STRESSES AND CALCULATED SATURATION STRESSES WITH OCTAHEDRAL AND CUBE SLIP CONSTITUTIVE MODELS ACTIVE, RENE N4, 760°C (DATA FROM REF. 5)

ORIENTATION	TENSION OR COMPRESSION	.02% YIELD STRESS (REF [37]) (MPa)	CALCULATED SATURATION STRESS (MPa)	|ERROR| (%)
[001]*	T	956	956	0
[001]*	C	-818	-819	.1
[011]*	T	748	752	.5
[011]	C	-905	-865	4.4
[$\bar{1}$11]*	T	817	827	1.3
[$\bar{1}$11]	C	-842	-828	1.7
[023]	T	695	705	1.5
[023]	C	-747	-741	.9
[$\bar{2}$36]	T	716	725	1.2
[$\bar{2}$36]	C	-714	-752	5.3
[$\bar{1}$45]	T	656	692	5.5
[$\bar{1}$45]	C	-792	-763	3.6

* CONSTANTS WERE DERIVED USING THIS DATA

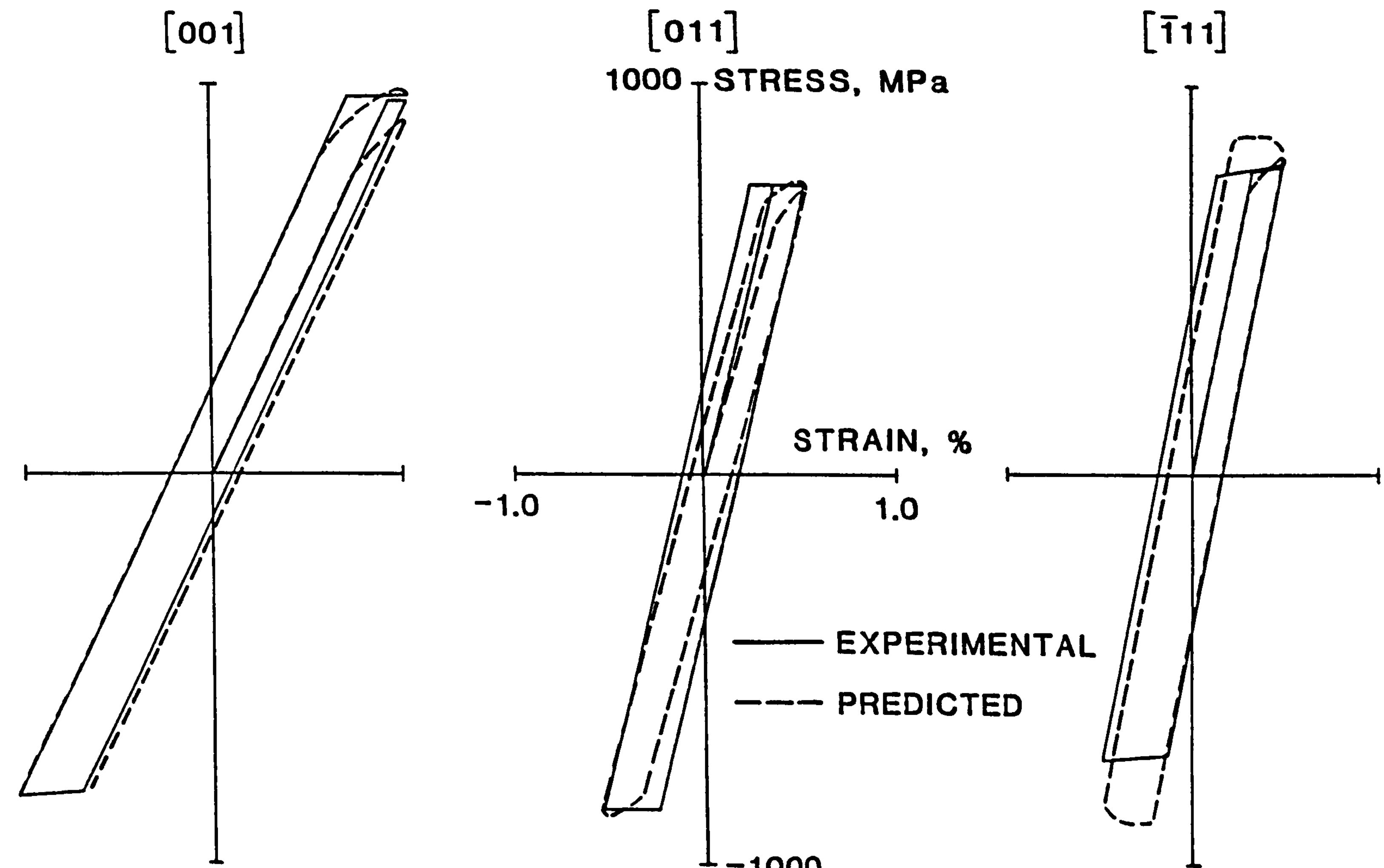

FIGURE 1 PREDICTED AND EXPERIMENTAL RESPONSE OF FIRST CYCLE FATIGUE LOOPS FOR RENE N4 AT 760°C, WITH KINEMATIC HARDENING (DATA FROM REF. 5)

C-4

FIGURE 2. PREDICTED AND EXPERIMENTAL STRESS STRAIN CURVES FOR RENE N4 VF317 AT 760°C. (DATA FROM REF. 6)

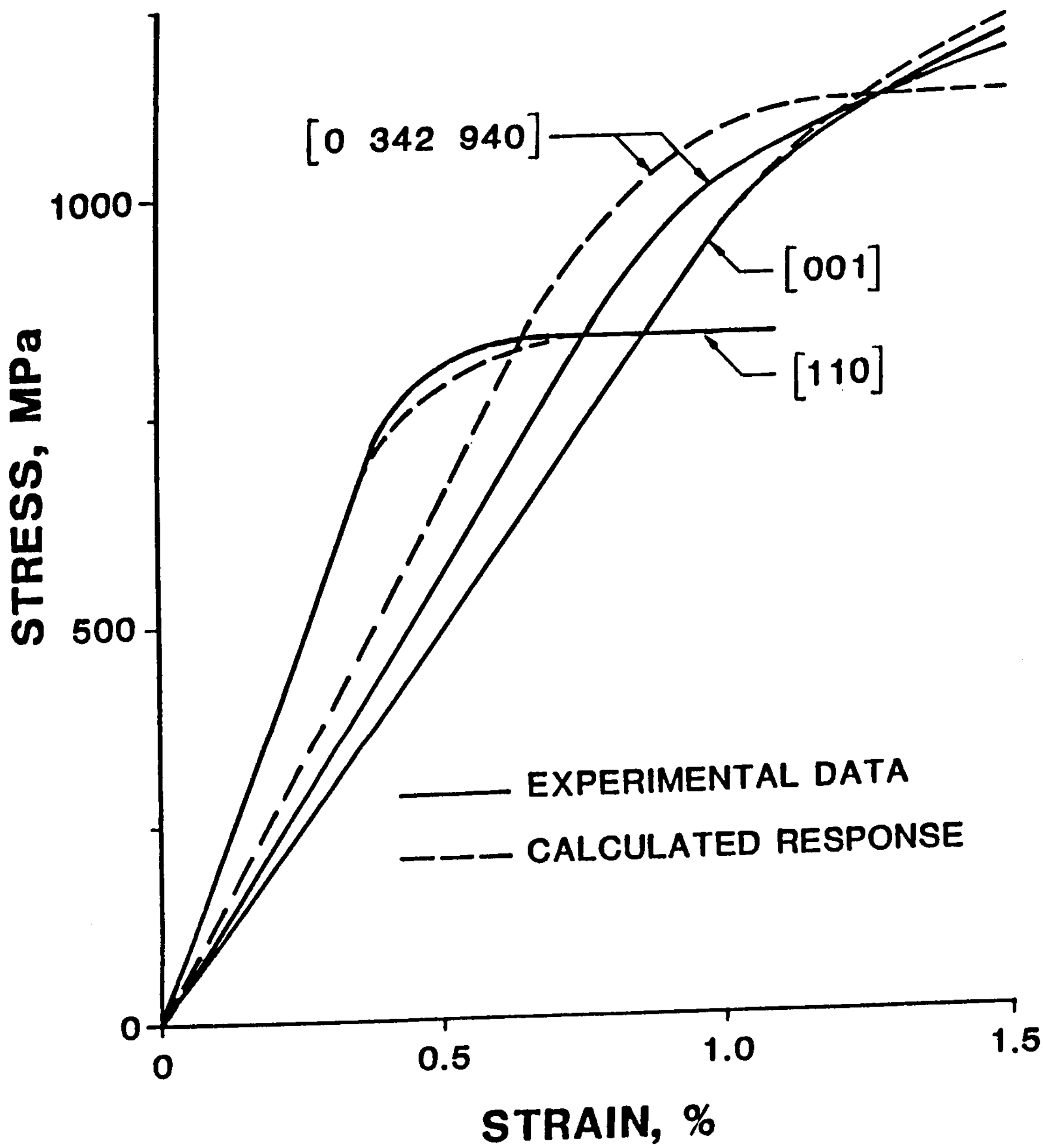

FIGURE 3. CREEP RESPONSE OF RENE N4 VF317 LOADED IN THE [001] DIRECTION AT 760°C. (DATA FROM REF. 6)